INVESTIGATION OF PRESSURE AND TEMPERATURE CHANGES AT THE BASE OF THE STRATOSPHERE

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1927

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Submitted in Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE
from the

Massachusetts Institute of Technology,

1937

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Department of Meteorology, May 18, 1937

Signature of Professor
in Charge of Research ______________________

Signature of Chairman of Department Committee
on Graduate Students ______________________

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INVESTIGATION OF PRESSURE AND TEMPERATURE CHANGES AT THE BASE OF THE STRATOSPHERE

I. Introduction

The object of this study is to investigate the pressure and temperature changes in the region of the Tropopause over stations in the United States and to attempt to seek relationships which might clarify or explain the reason for those phenomena that we know to exist in the upper Troposphere. We are particularly interested in those phenomena which give a variation of Tropopause height with a corresponding change of pressure at the nine kilometer level, and the temperature-height curves associated with such changes of atmospheric conditions.

Inasmuch as this investigation parallels closely those of W.H.Dines, Meteorologist in charge of Investigation of the Upper Air for the London Meteorological Office, and E. Palmen, Professor of the Meteorological Institute of the University of Helsingfors, in relation to the subject matter at hand, a brief resume will be given in order to explain the methods used and the results obtained by these two eminent meteorologists.

Especial thanks are due Professor C.G.Rossby of the Massachusetts Institute of Technology for his helpful advice in the preparation of this paper.

II. Investigations and Results of W.H.Dines.

The material upon which Dines based his investigations and conclusions consisted of upper air soundings over the British Isles and the Continent of Europe. He took departures from the mean of his sets of soundings and computed total and partial correlation coefficients and regression coefficients between sundry variables of the upper air. His variables were: 1. Pressure in millimeters at sea level. 2. Mean temperature of air column from the 1 to the 9 kilometer level. 3. The pressure at the 9 kilometerlevel. 4. The height of the Tropopause. 5. The temperature at the Tropopause. He defined the Tropopause height as that point where the decrease of temperature becomes 1 degree Centigrade or less per kilometer. The formula for obtaining his correlation coefficient was

$$r_{a,b} = \frac{\Sigma(\delta_a \delta_b)}{n \sigma_a \sigma_b}$$

where

$$\sigma_a = \frac{\sqrt{\Sigma(\delta_a)^2}}{n}.$$

and "a" and "b" represent the variables being correlated, " " the standard deviation, and "n" the number of ascents.

Dines has listed five sets of correlation coefficients obtained from a similar number of groups and

the British Isles. The correlation coefficients were obtained for all groupings by taking departures from the mean. The mean of the correlation coefficients for the entire five groups were computed and are as follows:

Surface pressure versus mean temperature	0.46
" " " pressure 9 km. level	0.66
" " " Tropopause height	0.69
" " " " temp.	-0.59
Mean temp. versus Pressure 9 km. level	0.92
" " " Tropopause height	0.78
" " " " temp.	-0.39
Press. 9 km. level versus Tropopause height	0.83
" " " " " temp.	-0.49
Tropopause height vs. Tropopause temperature	-0.65

He computed the standard deviations for his various sets of soundings and arrived at the following values for the mean of these standard deviations:

Surface pressure	9.4
Mean temperature	7.0
Pressure at the 9 km. level	9.2
Tropopause height	14.8
Tropopause Temperature	6.6

The units for these values are degrees Centigrade for the temperature, millimeters of mercury for the pressures,

and 100 meters for the tropopause height.

On the basis of the values of the correlation coefficients coupled with results obtained from partial correlation and regression coefficients, Dines arrived at the following conclusions:

1. The pressure at the 9 kilometer level has a positive effect on the surface pressure and the mean temperature. It is very closely and positively correlated with tropopause height, but he is not certain whether it is as cause or effect. It has a negative effect upon Tropopause temperature.

2. The temperature of the air column from 1 to 9 kilometers has a negative effect upon surface pressure, a large positive effect upon the pressure at the 9 kilometer level, no direct effect upon Tropopause height and a moderate positive effect upon Tropopause temperature.

3. Tropopause height has a positive effect upon surface pressure, no direct effect upon the mean temperature, it is closely correlated with the pressure at the 9 kilometer level, and has a very distinct negative effect upon Tropopause temperature.

4. Tropopause temperature has little effect upon any of the other variables.

III. Investigations of E. Palmen

The object of this study was to attempt to couple the important temperature and pressure variations in the lower stratosphere with the tropospheric distribution of these two variables. In this connection Palmen studied the effect of both thermal-advection and dynamic convection in relation to the coupling sought.

Palmen elected, as a means of investigating the advective process, to study the results of soundings made on both sides of the polar front. On one side he had Polar air, on the other, tropical maritime air. These soundings showed a temperature difference of about 15 degrees C. between the two air masses, this temperature difference attained its maximum value between the 4 and 7 kilometer levels. The tropopause in the polar air mass was around the 8 kilometer level, that in the tropical air around 12 kilometers. The temperature difference again became large in the vicinity of the 12 kilometer level; however, this difference was in a reverse order to the former, i.e., where the temperature of the tropical air had been higher in the troposphere, it was lower than that of the polar air, in

the stratosphere. Having obtained these results Palmen then proceeds to seek a coupling between the Polar front waves at the surface and the tropopause height changes.

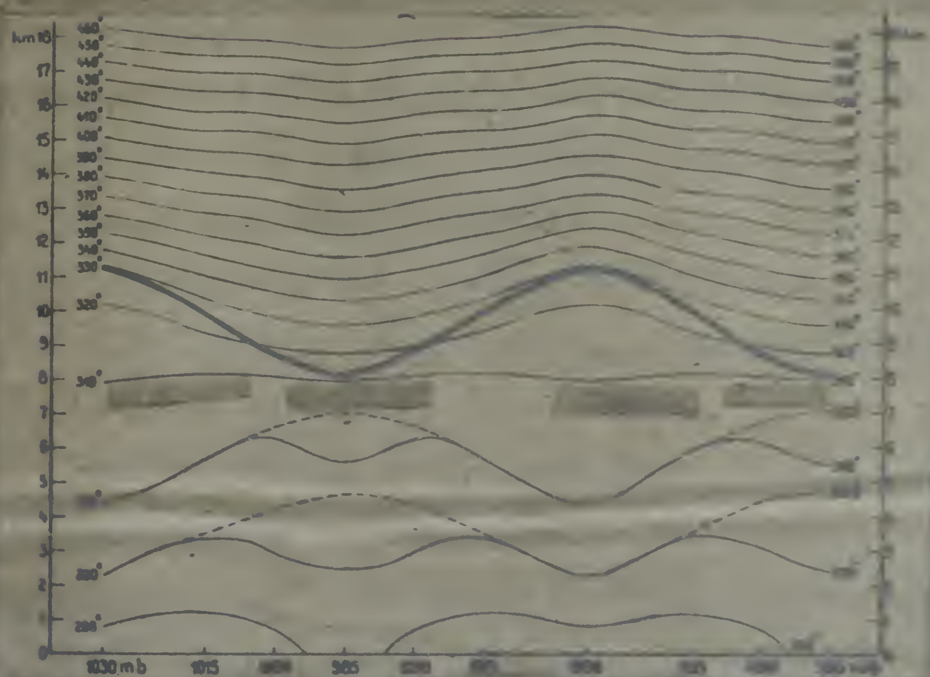
In the explanation of the coupling effect he parallels his ideas with those of Bjerknes. A wave is assumed to have formed on the polar front. The tropical air glides upward on the West side of all wave crests and downward on their East side. This forced vertical motion must die away with elevation, and it is known that it almost disappears at the tropopause. Accordingly, there is vertical shrinking over the West side of the polar front wave crests and corresponding horizontal divergence of the tropical air; on the East side, on the contrary, there is vertical expansion and horizontal convergence. The direct result of horizontal divergence is acceleration of anti-cyclonic circulation and the consequence of convergence is acceleration of cyclonic circulation. The original purely west-east flow of tropical air will therefore assume an anti-cyclonic curvature over the western slopes of the wave crests and a cyclonic curvature over the eastern slopes of the wave crests. The stream lines acquire a sinusoidal like shape in the horizontal - a shape which is also taken up by the isobars. The eventual resultant effect is to have a raising of the tropopause height over the part of the

flow with the northerly component, a sinking over that part of the flow with the southerly component. In the stratosphere is found, in turn, a vertical stretching and a vertical shrinking, in conjunction with the shrinking and stretching described above. The tropopause wave was found to be out of phase with the polar front wave, in that its corresponding amplitude points are to the westward of those on the surface.

Having reached this stage by means of thermal advection Palmen then demonstrates how the action of dynamic convection becomes the controlling factor.

The vertical motion is augmented by the increase of vorticity as the cyclone becomes more intense and occludes. The vertical shrinking is accompanied by a convergence of the potential temperature surfaces, the region of vertical stretching is accompanied by a divergence of the potential temperature surfaces with a convergence of these surfaces above the regions of stretching. In the regions of convergence we have a decrease of the temperature gradient. The action of the above is illustrated in the following sketch. (See Page 9). The positions of the points of maximum convergence represent the position of the tropopause in these regions.

Palmen further states that if the convergence of the potential temperature surfaces is super-


km 18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
460°
450°
440°
430°
420°
410°
400°
330°
320°
1030 mb
1015
985

imposed on the existing tropopause, it will cause the normal inversion found in this region to sharpen. He obtains three general types of temperature - height curves extending up into the stratosphere - or "tropopause types" - as are shown on the following sketch. (See page 11). For normal pressure, in this case 1007 millibars, is found an isothermal situation starting at the tropopause; for low pressure at the surface, 976 millibars, is found a sharp inversion of a depth of about 1 kilometer and then a gradual decrease of temperature with height; for high pressures at the surface, 1034 kilometers, is found a sharp inversion which extends several kilometers and then becomes practically isothermal.

If the action of the deformation field is such that the convergence of the potential temperature surfaces takes place other than at the tropopause itself, then, Palmen asserts, a new tropopause is formed at this region of convergence and the old tropopause is annihilated. The formation of this new tropopause, in sections at varying heights, gives a leaf-like structure, instead of a continuous smooth boundary surface. Turbulent mixing takes place between the open discontinuities of the new tropopause structure.

From the investigations and results as outlined above, Palmen arrives at the following conclusions:

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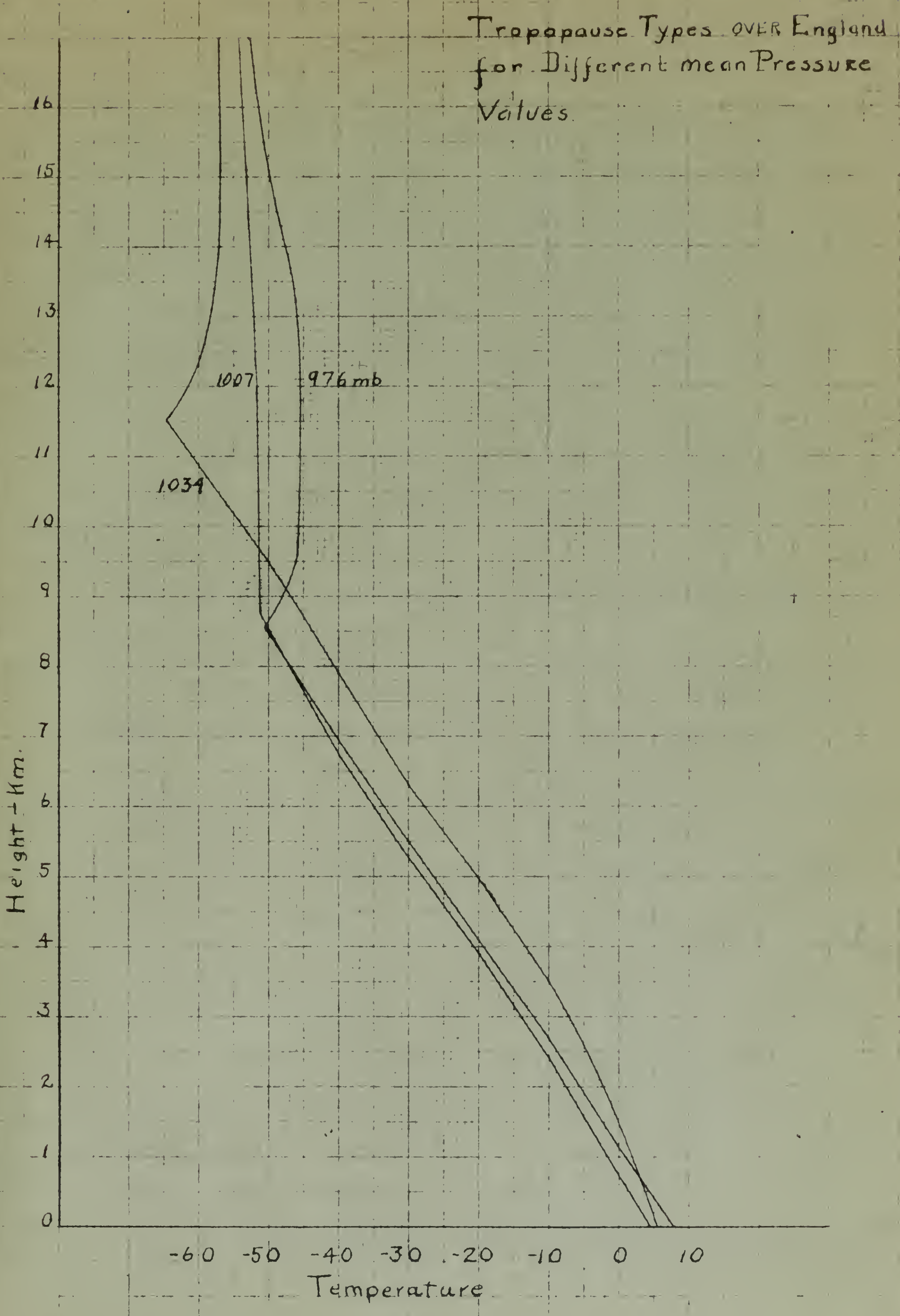
Tropopause Types OVER England
for Different mean Pressure
Values.
Height - Km.
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
1007
976 mb
1034
-60
-50
-40
-30
-20
-10
0
10
Temperature

1. In the primary development of a cyclone, advection dominates, in that the temperature changes in the main can be attributed to meridional advection - in this stage, polar front waves and tropopause waves are coupled in a certain phase displacement. The general tropopause and stratosphere advection represents a unified atmospheric flow pattern.

2. Investigation of temperature contrasts between tropical air and polar air gives the best means of study of meridional advection.

3. At times the frontal surface extends to the upper boundary of the tropopause.

4. As occlusion sets in a cyclone the dynamically vertical displacement dominates, in that, from this stage on, the temperature and pressure changes depend, in the main, on the vortification of the cyclone. A closer analysis of these temperature changes and of the vertical oscillations of the tropopause that one has to deal with, with the attendant deformation fields, show that not only tropopause types may change, but in certain cases the tropopause itself. From this it follows that the actually occurring vertical action in a so-called tropopause front may not always be determined from the oscillation of the apparent tropopause.

6. By investigating typical individual cases as

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6. By investigating typical individual cases as

well as through the formation of suitable mean values the influences of the fields of deformation of the temperature distribution in the environment of the tropopause over cyclones and anti-cyclones becomes quite clear. Over strong cyclones and occlusions the tropopause is generally characterized by a sharp inversion. This is also the case over anti-cyclones. There is an important difference in that the tropopause is low over cyclones and high over anti-cyclones. Also the tropopause inversion over cyclones covers about 1 kilometer while the inversion is several kilometers deep over anti-cyclones. At normal pressure the lower stratosphere over Europe is characterized by particularly isothermal stratification.

7. By the distribution of potential temperature one can, by omitting radiation and advection, in certain cases compute the vertical displacements which actually took place in the generation of highs and lows.

8. The question of the seat of atmospheric pressure variations can be answered only on the basis of detailed analysis of the phenomena at different levels. It is true that in general the stratosphere phenomena, on the face of it, have a deciding influence on the pressure variations below. But this fact depends on the general thermal structure of the atmosphere and has nothing to do with the problem of cause and effect.

IV. Analysis of Conditions Over Stations in the U.S.

The greatest obstacle to the proper development of this subject is the lack of sounding balloon ascents, not so much in quantity, but scarcity of soundings made at regular intervals over a period of time when large temperature and pressure variations are to be encountered. Also it was essential to use soundings which had been evaluated in a manner such that temperature, pressure, and elevation could be selected for a great number of points without having to recompute the soundings. The most desirable series of soundings were obtained for the stations listed below:

1.	Royal Center, Ind.	May 1926
2.	Groesbeck, Texas	Oct. 1927
3.	Broken Arrow, Okla.	Dec. 1929
4.	Royal Center, Ind.	Sep. 1930
5.	Royal Center, Ind.	Feb. 1931

This information was obtained from the various Monthly Weather Reviews.

All seasons except the summer are represented in this group, in addition there is a variation of latitude between the extreme stations of about ten degrees. Since some of the groups evaluated by Dines consisted of

soundings made throughout the year and at various stations in Europe, it is believed that reliable results can be obtained from the above stations.

It was necessary to select a system of grouping the soundings in pairs such that the maximum number could be obtained, since it was believed that satisfactory mean values could not be established accurately for the monthly periods. The groupings consisted in determining the changes between two subsequent soundings where the time interval between the two was not less than eight hours and not more than thirty hours. This irregular time interval was necessary because of the fact that the balloons were not released at constant intervals, a few of the records were lost or destroyed, and some of the soundings extended only a few kilometers above sea level.

In many of the soundings it was extremely difficult to determine the tropopause height, necessitating the formulation of an arbitrary definition for this height. The method used by Dines was selected, in which he defines the tropopause height as the highest point where the temperature decrease is less than one degree per kilometer. By adhering to a rule of this sort there is a tendency to eliminate all low inversions one of which may be the tropopause with a considerable

temperature decrease above the inversion. Therefore the results obtained by using tropopause heights and temperatures, cannot be judged so much by their numerical values but certainly the signs of the correlation coefficients should be correct.

The soundings were grouped for each station into pairs as explained above and the time variation of the various elements obtained. From these differences the standard deviations were computed by the formula

$$\sigma = \sqrt{\frac{\Sigma(\delta_a)^2}{n}} .$$

The values of the standard deviations are listed below:

Ps	4.5 mb.
Tm	3.4°C.
P9	4.4 mb.
Hc	1370 m.
Tc	6.1°C.

By comparing the standard deviations with the individual differences no ratio of the two was greater than 2.5 which shows that the material selected was very uniform.

The correlation coefficients were calculated from the standard deviations by means of the formula:

$$r_{a,b} = \frac{\Sigma(\delta_a \delta_b)}{\sqrt{\Sigma(\delta a)^2 \, \Sigma(\delta b)^2}}$$ where a, and b represent the variables being correlated. The correlation coefficients are listed below in addition to those obtained by Dines.

Number of Combinations	Items Correlated	Correlation Coefficients	Mean Correlation Coefficients-Dines
82	$r_{1,2}$	-.30	.46
80	$r_{1,3}$	.12	.66
52	$r_{1,4}$	.14	.69
52	$r_{1,5}$	.11	(-).59
80	$r_{2,3}$	.70	.92
52	$r_{2,4}$	.35	.78
52	$r_{2,5}$	(-).16	(-).39
52	$r_{3,4}$	.25	.83
52	$r_{3,5}$	(-).04	(-).49
52	$r_{4,5}$	(-).67	(-).65

1 = Surface Pressure

2 = Mean Temperature 1 - 9 km.

3 = Pressure 9 km.

4 = Height Tropopause

5 = Temperature Tropopause.

It will be noted that wherever Hc or Tc is involved as one of the variables, the number of groupings decreases. This is due to the fact that many of the soundings did not extend up to the tropopause.

It was believed that the extreme smallness of most of the correlation coefficients might be due to the method of grouping together stations in different latitudes and for different seasons of the year. Several of the individual months were grouped separately but the correlation coefficients obtained from these groups were of about the same magnitude as those found for the entire group, so that the correlation coefficients calculated from the entire group were accepted as being representative of the atmosphere over the United States.

The correlations which are of chief interest to synoptic meteorologists are those which may be deduced from surface observations. From the table it may be seen that surface pressure has a fair negative correlation with the mean temperature but practically no correlation with any of the other elements. This brings out very strikingly the independence of surface pressure. This is in direct opposition to the results obtained by Dines as may be noted from an inspection of the tables above. This difference may be explained by considering the disturbances observed over the United States and Europe. As a general rule cyclones and anticyclones occurring over Europe are very deep, well-developed disturbances, which in many instances are believed to extend well into the stratosphere.

Over the United States most of the surface disturbances are comparatively shallow and move fairly rapidly. This is apparent from the atmospheric cross-sections made at M.I.T. during the past winter.

The only marked agreement between the correlation coefficients of Dines and those obtained for the United States are those between mean temperature and the pressure at the 9 kilometer level, and between the tropopause height and the temperature at the tropopause. It is seen that with a high pressure at the 9 kilometer level there is a corresponding large increase in the mean temperature of the column of air under this level and for a low temperature at the 9 kilometer there exists a low mean temperature of the air column. This warming and cooling is of such a magnitude that it cannot be explained by this change of pressure so that other explanations had to be sought which are incorporated in that part of the investigation following the methods of Palmen. It is also seen that with a high tropopause there exists cold temperatures and with a low tropopause there exists warm temperatures. More detailed discussion of this condition will be given on the following pages.

Potential Temperature Surfaces in the Vicinity of the Tropopause and Tropopause Types Obtained from this Distribution Paralleling the Methods of Palmen.

The first step in the study of the distribution of potential temperature surfaces in the vicinity of the tropopause was to obtain correlation coefficients between the pressure at the 9 kilometer level and the heights of specific potential temperature surfaces. In selecting potential temperature surfaces it was deemed expedient to select surfaces close enough to the tropopause so that the contour of the latter could easily be compared to the contour of the former. At the same time it was necessary to use a range of surfaces which would clearly indicate any convergence or divergence and important temperature variations.

The material used consisted of the records for September 1930 and February 1931 for Royal Center, Indiana and for December 1929 at Broken Arrow, Oklahoma. The values for these correlation coefficients are tabulated on page 21.

BROKEN ARROW - DECEMBER 1929

θ	r	H_{mean}	$P_{\theta mean}$	Number of Pairs
315	(-).91	6,740	313	21
325	+ .51	9,995	310	16
335	+ .74	11,010	310	14
365	+ .81	13,200	309	13

ROYAL CENTER - SEPTEMBER 1930

θ	r	H_{mean}	$P_{\theta mean}$	Number of Pairs
320	(-) .53	5,620	323	24
335	(-) .40	9,300	324	17
350	+ .15	12,460	322	18
365	+ .65	13,820	324	15

ROYAL CENTER - FEBRUARY 1931

θ	r	H_{mean}	$P_{\theta mean}$	Number of Pairs
300	(-) .76	4,540	302	27
310	(-) .25	8,090	302	22
320	+ .26	9,960	302	20
330	+ .59	11,050	302	20
340	+ .74	11,510	302	18
360	+ .67	12,760	302	16

The number of pairs of soundings available for the individual months range from 27 for the lower surface to 13 for the extreme value of potential temperature. It is unfortunate that more soundings in sequence could not have been obtained, however, it is believed that they are adequate for the investigation at hand. A very consistent range of correlation coefficients was obtained for each individual month, being negative for low poten-

tial temperature values and positive for high potential temperatures. The magnitude of the correlation coefficients are large for the extreme values of potential temperature.

In order to show graphically the points brought out by the correlation coefficients, a plot of the pressure at the 9 kilometer level was made against the height of potential temperature surfaces. Over the low pressure there is a marked concentration of potential temperature surfaces. Over the high the tropopause is much higher and it has increased its potential temperature by some 20 degrees.

The curves discussed in this paragraph and those that follow will be found grouped by stations on pages 24,25,26,27,28,29.

In order to obtain the best average position for the tropopause, regression equations were deduced and regression lines for the various potential temperatures. These were superimposed on their respective potential temperature curves on the pressure-height plot.

The regression equation used was:

$$H = H_{mean} + r\sqrt{\frac{\Sigma(\delta h)^2}{\Sigma(\delta P_9)^2}}\,(P_9 - P_{9mean})$$

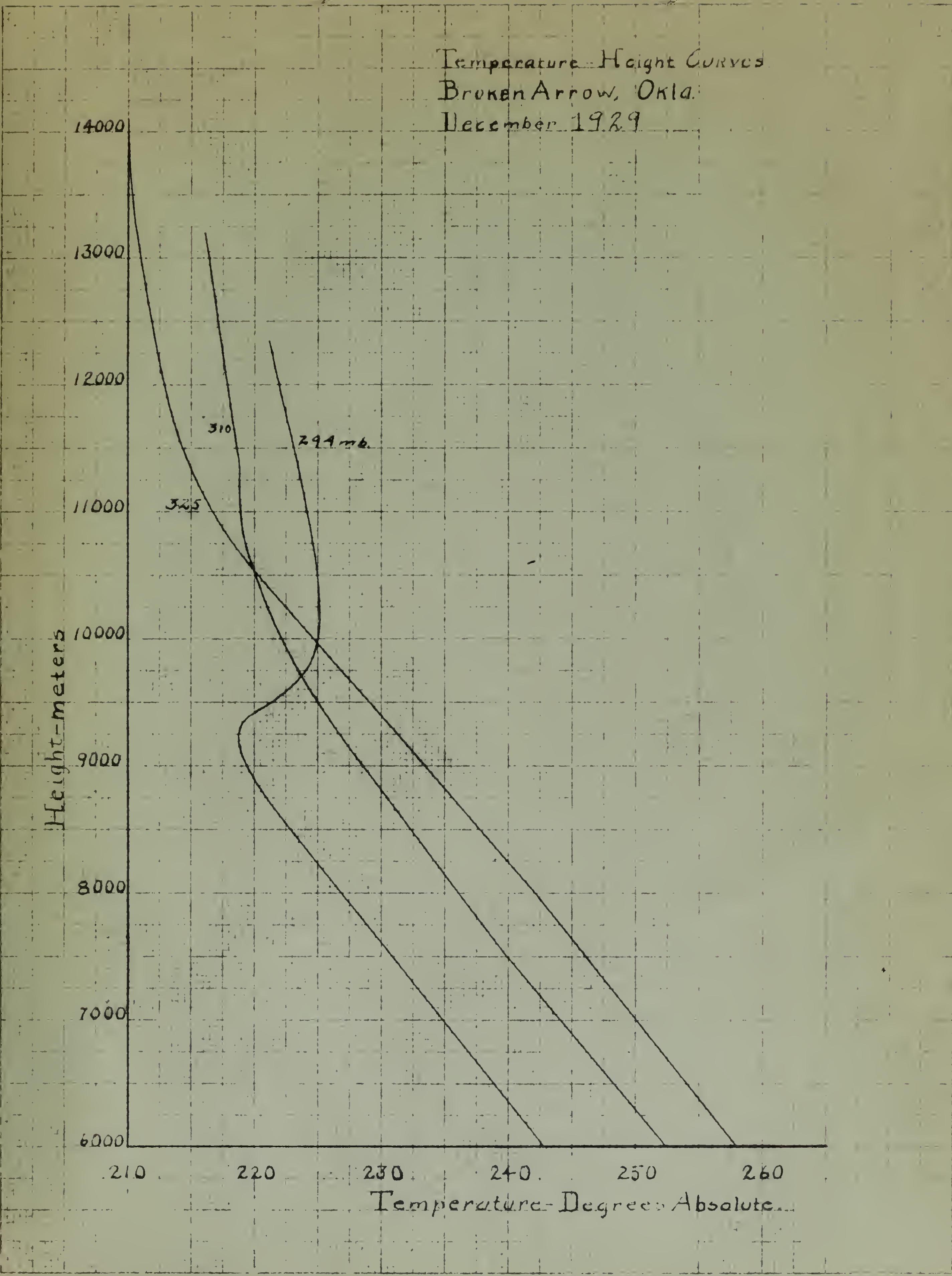
Characteristic temperature-height curves were plotted for the distribution of potential temperature regression lines for high, average, and low pressures at

the 9 kilometer level. The equation used to establish the temperature at different levels was formed from Poisson's equation and the hydrostatic equation:

$$T = \theta \left[\frac{P_9^{\,k}}{P_0^{\,k}} - \frac{g}{c_p} \frac{(Z - 9)}{T_{mean}} \right]$$ where θ = Potential Temperature.

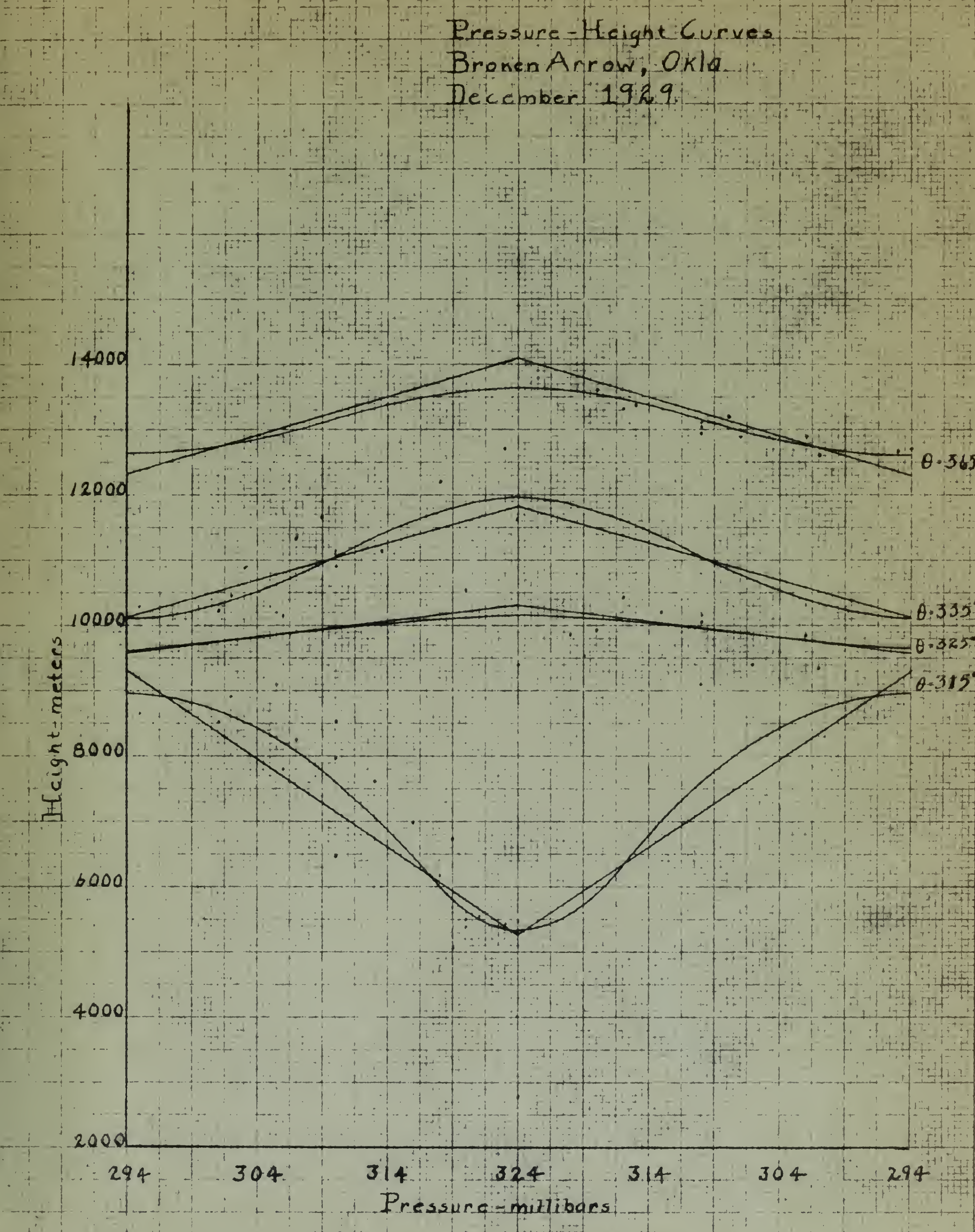
These temperature-height curves show that definite characteristic types of the tropopause inversion exist over high and low pressure areas at the 9 kilometer level. A marked similarity will be noted for the three cases analyzed. The inversions over low pressure are several kilometers lower than the mean height of the tropopause and are marked by fairly steep lapse rates in the troposphere below this inversion. Above the inversion there is a gradual decrease of temperature continuing as far as the sounding was extended. The tropopause over the high was not marked by a large inversion but gave a small rate of increase of temperature in the stratosphere.

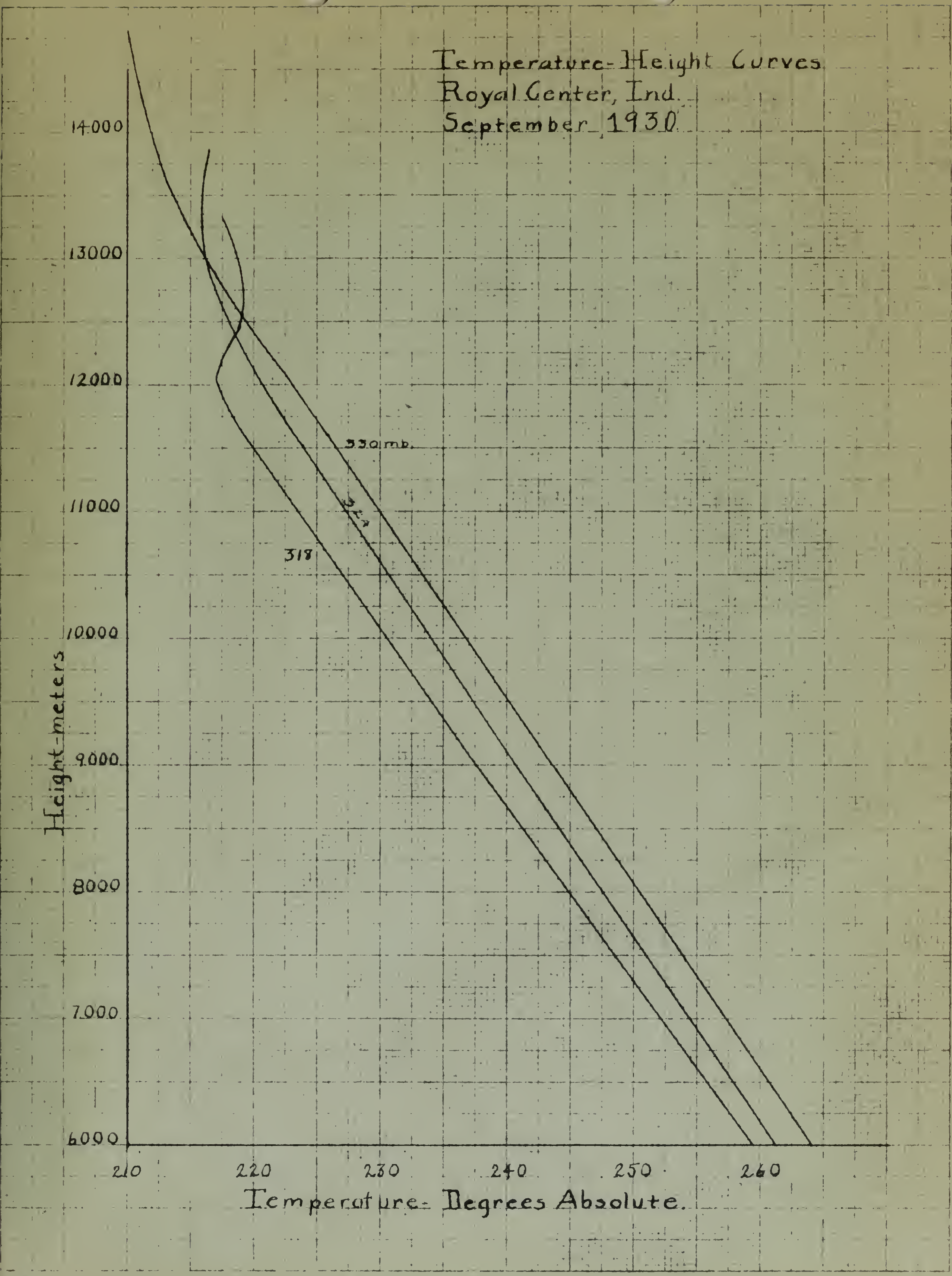
It is to be noted that the troposphere is about 8 degrees warmer under the high pressure than under the low. Above the tropopause the temperature over the high is considerably colder than that over the low. This distribution is exactly that found by Palmen, which has been accounted for by him through the influence of

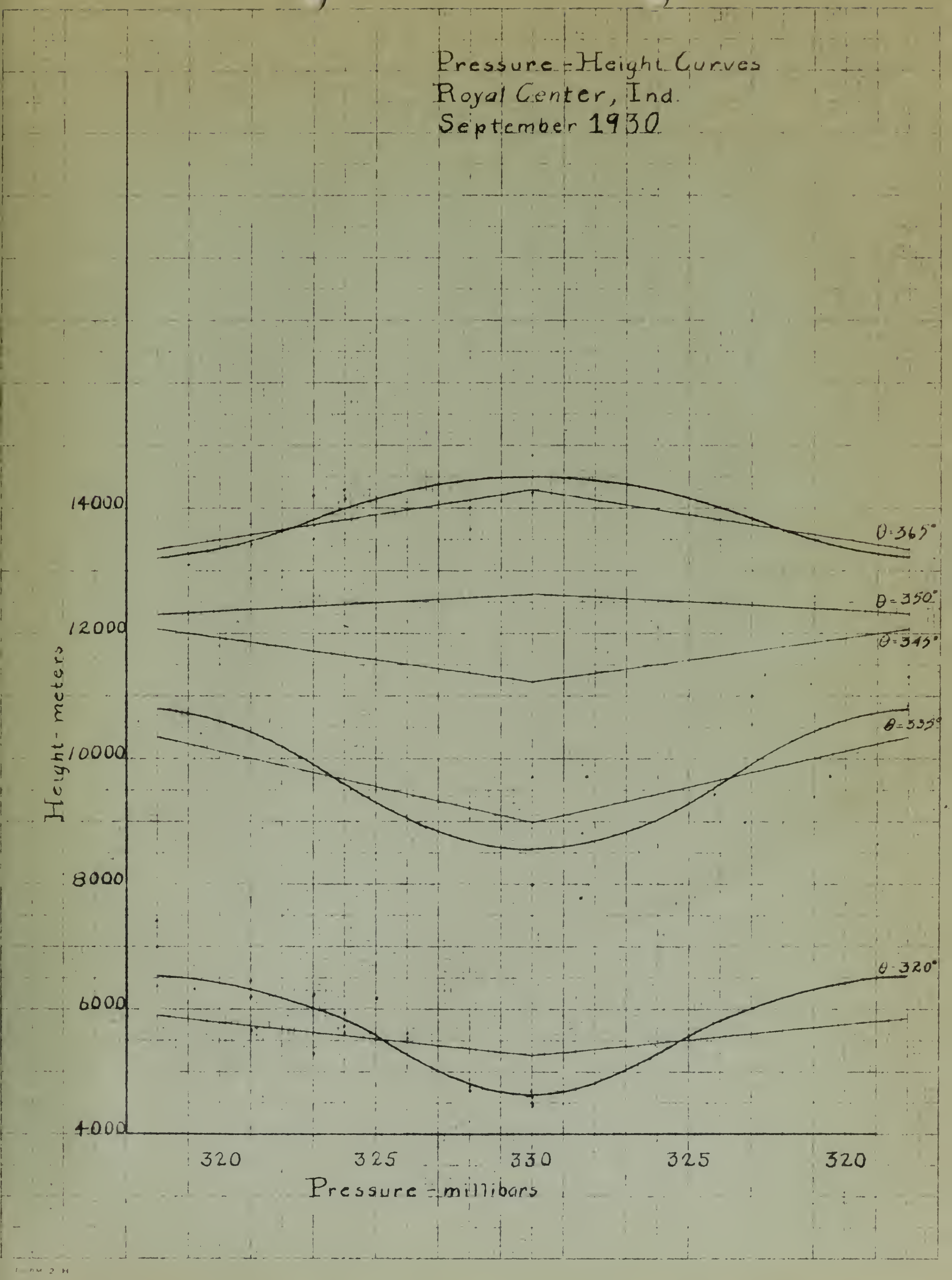


Temperature-Height Curves
Broken Arrow, Okla.
December 1929
14000
13000
12000
11000
10000
9000
8000
7000
6000
Height-meters
310
294 mb.
325
210
220
230
240
250
260
Temperature-Degrees Absolute

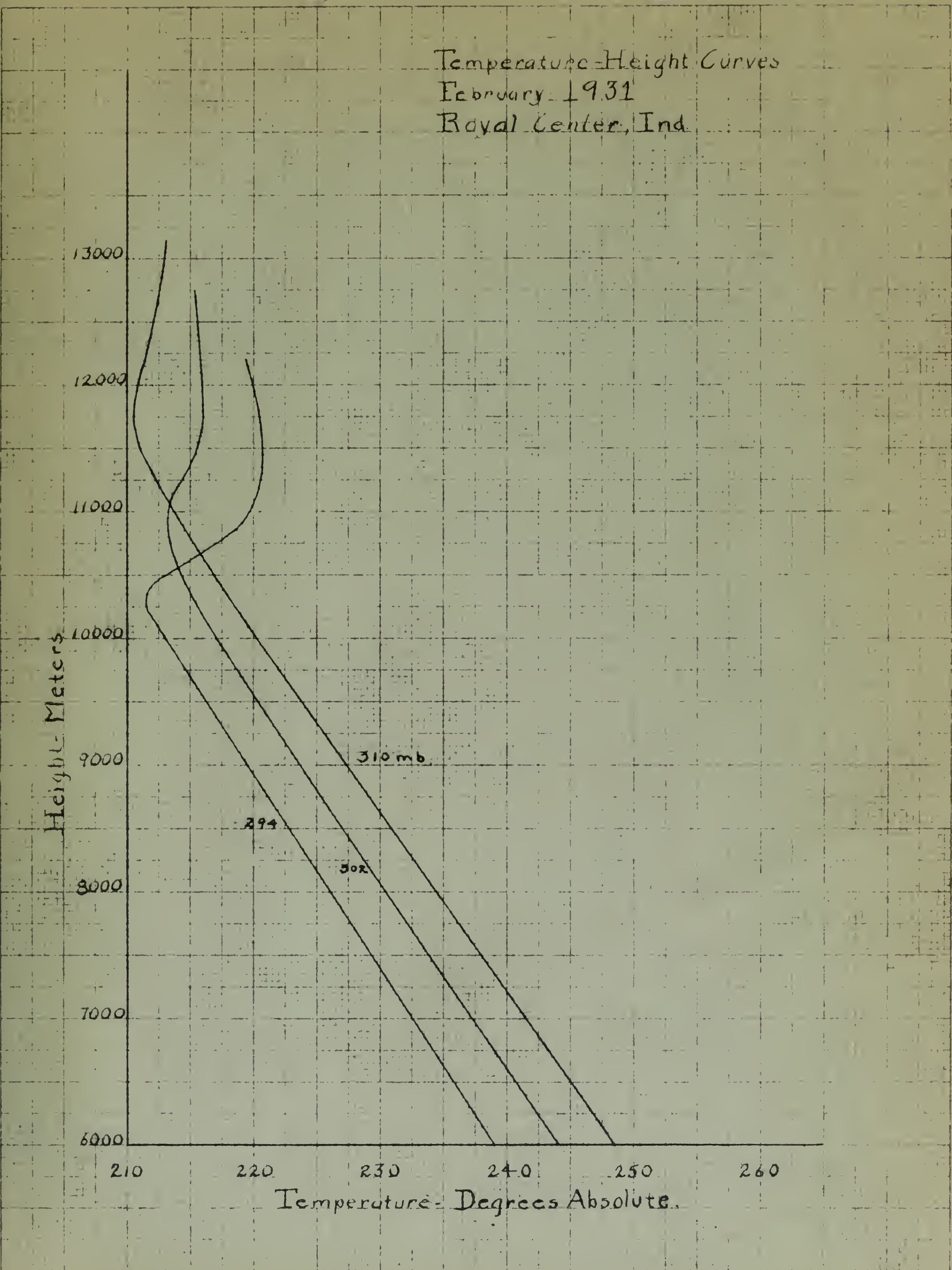
FORM 2 H


Pressure-Height Curves
Broken Arrow, Okla.
December 1929
Height-meters
14000
12000
10000
8000
6000
4000
2000
294
304
314
324
314
304
294
Pressure-millibars
θ-365°
θ-335°
θ-325°
θ-315°

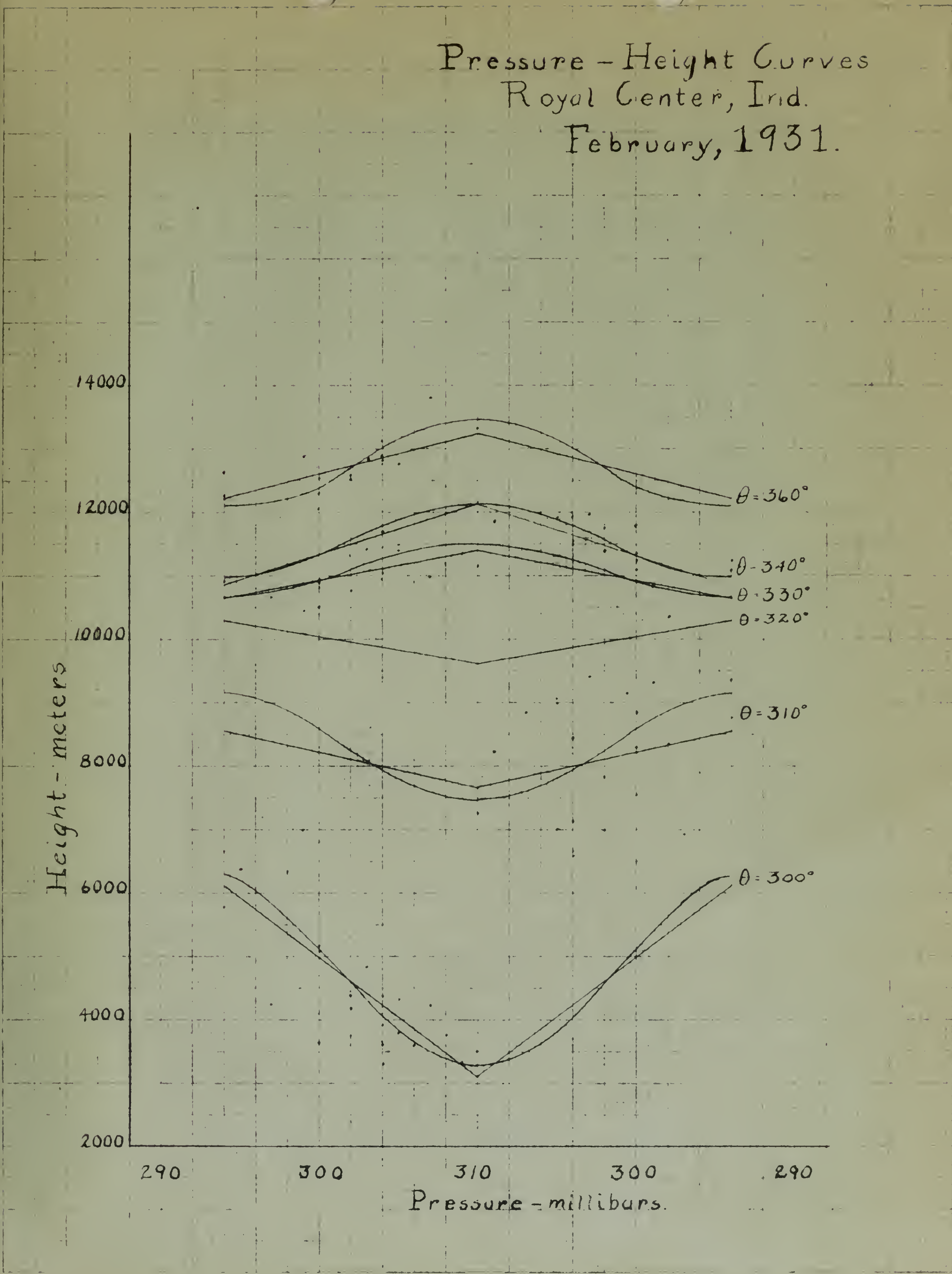

Temperature-Height Curves
Royal Center, Ind.
September 1930
14000
13000
12000
11000
10000
9000
8000
7000
6000
Height-meters
330 mb.
318
210
220
230
240
250
260
Temperature-Degrees Absolute.



Pressure-Height Curves
Royal Center, Ind.
September 1930
Height-meters
14000
12000
10000
8000
6000
4000
320
325
330
325
320
Pressure-millibars
θ=365°
θ=350°
θ=345°
θ=335°
θ=320°



Temperature-Height Curves
February 1931
Royal Center, Ind.
Height - Meters
13000
12000
11000
10000
9000
8000
7000
6000
310 mb.
294
302
210
220
230
240
250
260
Temperature - Degrees Absolute.


Pressure - Height Curves
Royal Center, Ind.
February, 1931.
Height - meters
14000
12000
10000
8000
6000
4000
2000
290
300
310
300
290
Pressure - millibars.
θ = 360°
θ - 340°
θ - 330°
θ - 320°
θ = 310°
θ = 300°

thermal-advective and dynamic processes as explained in the resume of his work.

From the above investigation the following conclusions have been drawn:

V. Summary

1. The contour of the potential temperature surfaces in the vicinity of the tropopause and in the stratosphere are very similar to the contour of the tropopause, while in the troposphere below the 9 kilometer level the slope of the former is opposite to that of the latter.

2. The existence of the tropopause types is substantiated by the distribution of the potential temperature surfaces. Over the low pressure area we have a well defined field of convergence, indicative of a region of great stability - over the high pressure area we find more equal spacing of the surfaces but, however, a gradual decrease in the distances between these surfaces - an indication of stability but to a lesser degree. The translation of the distribution of potential surfaces to a temperature versus height diagram shows in more detail the actual amount of stability represented.

3. The displacement of the concentration of potential temperature surfaces to a different level causes the regeneration of the tropopause at that level. We have a condition where the instantaneous height of the tropopause cannot be defined as existing at one

height only. The shifting of the tropopause to different levels has its origin in the thermal-advective processes.

4. The tropopause height varies as the pressure at the 9 kilometer level. Little correlation exists between the pressure at the surface and that of the 9 kilometer level, hence there is little correlation between surface pressure and tropopause height. The transitory nature of the shallow-disturbances which traverse the United States would account for this variation from European conditions.

5. The tropopause type curves show definitely that the troposphere temperature for a high pressure at the 9 kilometer level is considerably higher than that for a low pressure at the same level. In the stratosphere the opposite effect is true, i.e., over the high it is colder than over the low. This distribution of temperature is accounted for primarily by advection but intensified in the vicinity of the tropopause by convection especially over a low pressure area.

6. An examination of the zonal distribution of pressure and temperature at different heights indicates that the conditions outlined as existing over the United States could be accounted for primarily by thermal-advection but that convection is required to complete the picture.

7. The temperature height curves for Royal Center, February 1931 show the temperature at the base of the inversion for the low pressure curve to be low and practically the same as that for the same relative position on the high pressure curve. This phenomenon is difficult to explain, however, the curves in general, demonstrate the existence of strong convection over a cyclone and a resultant cold tropopause temperature.

In connection with this idea, it is known that when polar continental air leaves its source region and crosses an open ocean surface, violent convection ensues. It is probable that, initially, when air temperatures are very low, this convection extends to about 8 or 9 kilometers. When this polar maritime air passes over land the convection phenomenon is diminished and the tendency towards the restoration of radiation equilibrium is strengthened. If in this case, we had a very strong flow of polar pacific air it is probable that the results indicated by the temperature-height curve represents that state where the convection process is still felt giving the extremely low tropopause temperature and a tropopause height slightly higher than normal conditions would warrant.

Reference to the daily sounding-balloon ascents made at Royal Center during the month shows several cases where there exists extremely steep lapse rates below the

level of the tropopause and in the vicinity thereof, with marked inversions present just above the tropopause. A thorough and comprehensive study of this problem necessitates the investigation of the predominant wind direction. For the soundings cited, this essential data was missing in the majority of cases.

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Thesis
D76 Drouilhet 32850
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